90° LASER LIGHT SCATTERING FROM A LOW DENSITY PLASMA

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THESIS

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ABSTRACT

This experiment was conducted to learn experimental techniques for studying Thomson Scattering at an angle of 90° from a laboratory plasma. A successful method of canceling the plasma radiation was employed by using a Calcite Slab to separate the plasma radiation into two equal intensity beams which self canceled when put through a differential amplifier. Scattered light from the plasma was not observed due to the noise level of the photomultipliers and the reflections from the plasma chamber.

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I. INTRODUCTION

Since the invention of the laser in the 1950's, people have been looking for new ways to use the laser as a tool for scientific research. Laser scattering experiments have been conducted since the early 1960's. The laser with its capability to produce high power levels in extremely short time intervals has been found to be an excellent tool for measuring a plasma's density and temperature.

This experiment is a continuation of the effort to develop Thomson scattering as a method for the studying of the plasmas produced at the United States Naval Postgraduate School's Plasma Facility. In the future this technique will be used to study laser produced plasmas and θ-Pinch plasmas. Previous work was done by LTJG Alfred A. Pease. His results are contained in his Master's Thesis, "Laser Light Scattering as a Plasma Diagnostic Technique" [Ref. 1]. LTJG Pease's work was accomplished using a different experimental detection apparatus. An Optics Technology, Model 130, high peak power, Q-switched ruby rod laser was used in both of our experiments. The reasons for changing the experimental detection apparatus are explained in Section III.

Thomson scattering at an angle of 90° was chosen for various reasons. The first of these being the need to develop a technique that can be used anywhere along the plasma column. The Plasma machine (Figure 1) consists of a long vacuum chamber with ports for diagnostics which are easiest used for 90° scattering experiments. A 90° scattering is also preferrential to a small angle scattering experiment in that precise spectra can be obtained [Ref. 2].

It is believed that the major difficulty in observing scattered light is caused by the inability of the available equipment to do the job. The Optics Technology Model 130 is a reliable laser when used in the non Q-switched mode. As a Q-switched laser it is unreliable and does not have the capability of producing the same pulse in two successive shots. This is due to the fact that it is Q-switched by the use of a liquid dye. Liquid dye has the fault that it deteriorates with successive firings. The liquid dye also allows prelasing and many times instead of one giant pulse it would put out two lesser pulses. A water cooled laser head which will be Q-switched by a Pockel's Cell is being made at the Plasma Facility. This new laser should greatly enhance the scattering experiment's chance for success in the future.

II. BACKGROUND

During the past several years various scattering experiments have been performed to investigate the density and temperature of laboratory produced plasmas. Thompson and Fiocco worked on the scattering of laser light from a low density, low temperature plasma. Their results showed that the ratio of scattered power to input power was on the order of 10^{-15}. This corresponds to an electron density $n_e \simeq 10^{13} cm^{-3}$, an electron temperature $T_e \simeq 1eV$, and a scattering parameter $\alpha \simeq 0.03$. In their experiment Thompson and Fiocco took advantage of the Doppler shift due to the high velocity of the electrons (small angle scattering was used) [Ref. 2]. The major problem involved with looking for the scattered light signal from a low density plasma, $n_e \simeq 10^{13}$ cm^{-3}, is that the background plasma noise is greater than the intensity of the scattered light. Since this experiment involves right angle scattering, it was necessary to employ a method to either reduce or eliminate the background noise. Filters can not be used because even though they reduce background noise, they also reduce the intensity of the scattered light.

LTJG Alfred A. Pease, USN, worked at right angle scattering while at the United States Naval Postgraduate School [Ref. 1]. In his experiment, LTJG Pease took advantage of the idea that a sharply tuned source in conjunction with a narrow band detector could negate the background radiation. This type of experiment using a 3-meter spectrograph and photomultipliers has many obvious advantages but it also has one disadvantage. This being that the optical alignment necessary to eliminate the plasma self-radiation (background noise) and insure maximum

effectiveness of all components becomes extremely difficult and unreliable. Since the primary objective of theses initial experiments is to detect scattered light with positive assurance that the scattering is Thomson scattering from the plasma, the 3-meter spectrograph was discarded in favor of a setup which is easier to optically align and can initially use a wider band detector. Of course, this means that the plasma self-radiation must be considered and disposed of in an acceptable manner.

The plasma radiation may be of three types; bremsstrahlung (free-free transitions), recombination radiation (free-bound transitions), and line radiations (bound-bound transitions). Since all three types of radiation will appear in various intensities, all must be considered. This experiment was conducted between the cathode and anode of the plasma machine. For bremsstrahlung radiation the total emitted power in watts per unit volume between wave lengths λ and $\lambda + d\lambda$ is $\varepsilon_\lambda d\lambda$ where, [Ref. 3],

$$\varepsilon_\lambda d\lambda = 1.9 \times 10^{-28} N_e N_i Z^2 \bar{g} \frac{1}{\sqrt{KT_e}} \frac{1}{\lambda^2} \exp\left(\frac{-12395}{\lambda KT_e}\right) d\lambda \ W_\lambda/cm^3$$

Where N_e = electron density

N_i = ion density

Z = nuclear charge

$\bar{g}$ = gaunt factor

KT_e = electron temperature in eV

W_λ = scattered intensity

λ = incident wavelength in Å.

This is a unwieldly relationship, but it is used in calculating the ratio of scattered light to plasma radiation [Ref. 3].

$$\frac{W_\lambda}{P_\lambda} = 4\pi \left(\frac{d^2\sigma}{d\Omega dx}\right) \frac{L_\lambda}{\varepsilon_\lambda} \frac{dz}{V} \frac{d\Omega_S}{d\Omega_P} .$$

where L_λ = incident power

d = length observed in plasma

V = volume in the plasma from which plasma radiation in the solid angle $d\Omega$ goes into the receiver

W_λ and P_λ have units of power.

With Thomson Scattering at 90°, the above can be shown to be

$$\frac{W_\lambda}{P_\lambda} \propto \frac{\lambda}{N_e} L_\lambda .$$

From this it can be seen that the ratio of scattered light to plasma radiation for a fixed input power and wavelength will increase as the density decreases. The ratio will also increase if the input power is increased. By looking at the relationship between scattered and incident power, [Ref. 2],

$$\frac{W_\lambda}{L_\lambda} = \sigma_e N_e S(k) dz d\Omega,$$

where σ_e = electron cross section for Thomson Scattering

$S(k)$ = form factor

it is clear that low densities are not desirable. The problem, of course, is not to measure the plasma radiation, but to dispose of it.

Therefore the method of canceling out the background noise as developed by E. Funfer, B. Kronast, and H. J. Kunze was used [Ref. 2]. In their experiment, this group was working on scattered light from a high density θ Pinch ($n_e \simeq 10^{17}$ cm^{-3} and $T_e \simeq 5$ eV). Although this plasma density and temperature gives a much better ratio of scattered to input power, about 10^{-11}, the intensity of self-radiation of the plasma was found to still be much larger than that of the scattered light. Since Funfer et al. applied their method to a high density

plasma and the present experiment is with a low density plasma certain modifications have been necessary. Figure 2 shows the setup used by Funfer et al. while Figure 3 shows the laboratory setup used in the present experiment.

By taking advantage of the fact that the scattered light is plane polarized while the plasma self-radiation is not, a differential amplifier was used to cancel out the plasma self-radiation as shown, for example, in Figures 4 and 5. Figure 4 shows the plasma self-radiation signal on the oscilloscope with the Tektronix Plug-In unit 1A1 Input in the CHOP mode. The beam splitter was adjusted so that each channel (photomultiplier) receives one-half of the plasma self-radiation. Figure 5 shows the signal from the two photomultipliers (one has been inverted) with the 1A1 Input in the ADD mode. The plasma self-radiation's unpolarized state is taken advantage of by first dividing the light into two polarized beams and inverting one of the photomultiplier outputs so that the two beams add to give zero deflection on the oscilloscope.

The laser being used in the present experiment can be used to obtain an output power of approximately 50 Megawatts in the Q-switched mode. If the ratio of scattered to input power is 10^{-11}, then the scattered power will be

$$50 \times 10^{6} \text{ watts} \times 10^{-11} = 50 \times 10^{-5} \text{ watts}$$

By using RCA 7102 photomultiplier tubes with a sensitivity of 400 amps/watt, the current to the oscilloscope becomes

$$50 \times 10^{-5} \text{ watts} \times 400 \frac{\text{amps}}{\text{watt}} = 2 \times 10^{-1} \text{ amps}$$

If a 50 ohm resistor is used (to serve as a matching resistor), then the voltage shown on the oscilloscope will be

$$50 \text{ ohms} \times 2 \times 10^{-1} \text{ amps} = 10 \text{ volts.}$$

However, the plasma produced at the USNPGS Plasma Facility has been found to be on the order of 10^{13} cm^{-3} [Ref. 4] in the main chamber. At the cathode end with a smaller diameter of the plasma beam the density is estimated to be of the order of 10^{14}. As previously stated the relationship between scattered and incident intensity is, [Ref. 2]

$$\frac{W_\lambda}{I_\lambda} = \sigma_e N_e S(k) dz d\Omega$$

By letting

$$\theta = 90° \qquad S(k) = 1$$

$$dz = 1 \text{ mm}$$

$$d\Omega = 10^{-3}$$

$$\sigma_e = 0.67 \times 10^{-24}$$

$$N_e = 10^{14}$$

$$\frac{W_\lambda}{I_\lambda} = 0.67 \times 10^{-24} \times 10^{14} \times 1 \times 10^{-2} \times 10^{-3}$$

$$\frac{W_\lambda}{I_\lambda} \simeq 10^{-15}$$ for laboratory plasma at Plasma Facility.

By completing the same calculations as before it is shown that the voltage rise on the oscilloscope will be 10^{-3} volts.

Since the available differential amplifiers do not have the high gain necessary to see a 1 mV signal, it is necessary to use a larger input resistor. Although the larger impedance input will distort the time base of the signal, it will make it possible to see the signal above the photomultiplier noise. A 5 megaohm resistor was chosen. This not only gives a high input impedance but also provides a D.C. path to ground so that A.C. input can be used. Therefore, it is not

necessary to be concerned with the high D.C. level of the plasma radiation (received and amplified by the photomultiplier to ~ 30 volts). Now by balancing the photomultiplier it is possible to cancel out the fluctuating plasma light in the differential amplifier plug-in units down to the uncorrelated noise level.

III. THEORY

A. THOMSON SCATTERING

A more detailed discussion of this theory can be found in Ref. 2. By considering a scattering electron initially at rest and no magnetic field present, the equation for the incident plane wave is

$$\underline{E}(\underline{r},t) = \underline{b}\, E_0 \exp\{-i\,(\omega_0 t - \underline{k}_0 \cdot \underline{r})\}. \tag{1}$$

where E_0 = amplitude of oscillation

$\underline{b}$ = unit vector of polarization

$\underline{k}_0$ = propagation vector

ω_0 = angular frequency

This causes the electron to act as an radiating dipole with an equation of motion

$$\dot{\underline{U}}(t) = \underline{b}\,\frac{e}{m}\, E_0 e^{-i\omega_0 t}. \tag{2}$$

Since the radiation from an accelerated particle is (for $(r >> \lambda)$ and $(v << c)$

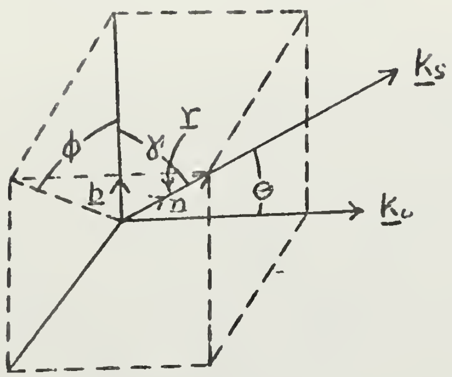
$$\underline{E}(\underline{r},t) = \frac{1}{4\pi\varepsilon_0}\;\frac{e}{c^2 r}\,(\dot{\underline{V}} \times \underline{n}) \times \underline{n}\,. \tag{3}$$

where $\underline{n}$ = unit vector in the direction of detection. By using Equations (1) and (2) the scattered radiation field becomes

$$\underline{E}_s(\underline{r},t) = \frac{1}{4\pi\varepsilon_0}\;\frac{e^2}{mc^2}\;\frac{1}{r}\;E_0 e^{-i\omega_0 t}\;(\underline{b} \times \underline{n}) \times \underline{n} \tag{4}$$

In this case, the frequency of the scattered radiation is the same as that of the incident wave and the radiation has characteristics of a dipole. By letting $r_0 = \frac{1}{4\pi\varepsilon_0}\,\frac{e^2}{mc^2}$ and $|(\underline{b} \times \underline{n}) \times \underline{n}| = \sin\theta$ the $|\underline{E}_s|$

$$E_s = \frac{r_0}{r} E_0 \sin\theta \tag{5}$$



The scattering cross section ($d\sigma$) can be found by the ratio of power scattered into the solid angle $d\Omega$ to the average incident flux ($\overline{S}_0$)

$$d\sigma = \frac{I_s r^2 d\Omega}{S_0} \ . \tag{6}$$

Since $\overline{S}_0 \propto E_0^{\ 2}$ and $\overline{I}_s \propto E_s^{\ 2}$ it is seen that (6) becomes

$$\frac{d\sigma}{d\Omega} = r_0^{\ 2} \sin^2\theta = \sigma_e .$$

where σ_e = cross section for scattering of electromagnetic waves by a single electron. The Thomson cross section can be found by integrating over the entire solid angle.

$$\sigma_{TH} = \frac{8\pi}{3} r_0^{\ 2}$$

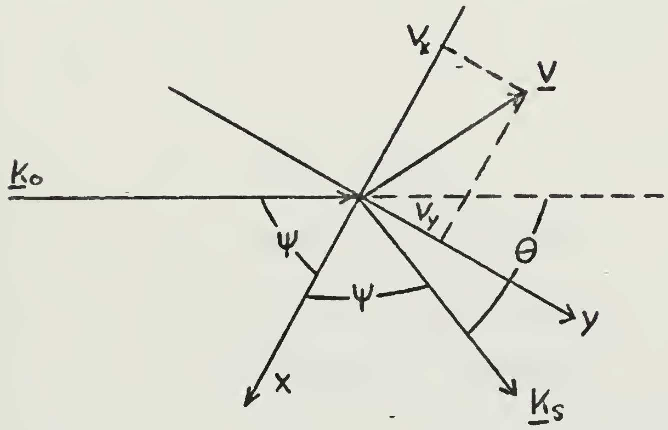
In this experiment $\theta = 90°$ and the incident radiation is plane polarized. Therefore, the scattered radiation will also be plane polarized.

B. DOPPLER SHIFT IN FREQUENCY

Since in reality, the electron does have an initial velocity ($\underline{V}$), a Doppler shift of frequency of the scattered radiation will be seen. By considering the scattering process to be in the plane of the particle,

the incident wave and the direction of observation; and the velocity $\underline{V}$ of the electron to have components V_x, V_y, and V_z, the velocity of the electron in the direction $\underline{k}_o$ is given by

$$V_{k_o} = - V_x \cos \psi + V_y \sin \psi$$



This means that the electron sees an incoming wave of frequency

$$\omega' = \omega_o - \frac{\omega_o}{c} (-V_x \cos \psi + V_y \sin \psi).$$

Also the velocity of the electron in the direction $\underline{k}_s$ is

$$V_{k_s} = V_x \cos \psi + V_y \sin \psi$$

and the shifted frequency is given by

$$\omega_s = \omega' + \frac{\omega_o}{c} (V_x \cos \psi + V_y \sin \psi).$$

Therefore the Doppler shift ($\Delta\omega = \omega_s - \omega_o$) is

$$\Delta\omega = \frac{\omega_o}{c} \; 2 \, V_x \cos \psi = \frac{\omega_o}{c} 2V_x \sin \; \frac{1}{2}\theta \quad (\psi = 90'' - \frac{1}{2}\theta)$$

For small Doppler shifts, i.e., $|\underline{k}_o| \simeq |\underline{k}_s|$

which allows the Doppler shift to be written as

$$\Delta\omega = \underline{k} \cdot \underline{V}$$

It must be noted that only the frequency of scattered radiation not the scattering cross section is changed.

C. THEORETICAL RESULTS

Since the scattering is considered to be Thomson Scattering, there will be no correlation between the scattering electrons. This approximation depends on the parameter

$$\alpha = \frac{1}{|\underline{k}|D} .$$

where $D = \sqrt{\dfrac{KT_e}{4\pi n_e e^2}}$

D = Debye length

n_e = mean electron density

T_e = electron temperature

K = Boltzmann's Constant

For $\alpha \ll 1$ the assumption is fulfilled. Previous measurements taken on the plasma at the Plasma Facility have shown $n_e \approx 10^{13}$ cm^{-3} and $T_e \approx 8$ eV [Ref. 4]. This gives an $\alpha \approx 0.535$ which is less than 1 and the above assumption should hold. T_e was measured as 4.2 ± 0.2 eV in main body of plasma. $T_e \sim 8$ eV assumed between cathode and anode. Since $\frac{d\sigma}{d\Omega} = n_e \sigma_e = n_e r_o^{\ 2} \sin^2\theta$ ($\frac{d\sigma}{d\Omega}$ is now scattering cross section per unit volume), the contributions of all the electrons must be added to obtain a frequency distribution. In the normal case of equilibrium, the electrons will have a Maxwellian distribution according to the electron temperature T_e

$$dn_e \sim \exp\left(\frac{-mv^2}{2KT_e}\right) dV.$$

By using the equation for the Doppler shift ω a Gaussian profile will be obtained for the spectrum $S_t(\underline{k},\omega)$ of the scattered radiation (normalized to n_e)

$$S_T(\underline{k},\omega)\, d\omega = n_e \sqrt{\frac{m}{2\pi k^2 KT_e}} \; \exp\left(\frac{-m\omega^2}{2k^2 KT_e}\right) d\omega$$

The half-width of the Gaussian profile depends only on the electron temperature, i.e.,

$$\Delta\omega_{\frac{1}{2}} = 4\omega_o \sin\frac{1}{2}\theta \sqrt{\frac{2KT_e}{mc^2} \ln 2}$$

or

$$\Delta\lambda_{\frac{1}{2}} = 4\lambda_o \sin\frac{1}{2}\theta \sqrt{\frac{2KT_e}{mc^2} \ln 2}.$$

It should be noted that the electron temperature can be found without exact measurements of intensity and that the intensity can be plotted in arbitrary units.

To determine the electron density (n_e) is much more difficult since absolute intensities must be known. The necessary relationship is from above

$$S_T(\underline{k},\omega) = n_e \left(\frac{m}{2\pi k^2 KT_e}\right)^{1/2} \exp\left(\frac{-m\omega^2}{2k^2 KT_e}\right) .$$

IV. EXPERIMENTAL APPARATUS AND CALIBRATION

A. APPARATUS

As previous stated the experimental apparatus (Figure 3) is very similar to that first used by Funfer et al. [Ref. 2]. Beginning with the ruby laser the path of light after scattering is through the periscope (internal lens A is adjusted for parallel light) to the second lens B, which refocuses the light on the monochromator slit. The light there follows the path shown in Figure 3 and emerges from the monochromater at a right angle to the input. Lens C is set to focus the light on the Calcite slab. The Calcite slab has the property that it causes the light to be split into the extraordinary and ordinary wave polarizations. This slab is the one most important component of the experimental apparatus. Since the ruby laser not only gives off light of a fixed frequency, but also of a fixed polarization, the Calcite slab divides the light from the monochromator into one component polarized in the same direction as the scattered light and one component polarized perpendicular to the scattered light. Now by the use of the beam splitter, the light of each polarization is seen by a different photomultiplier tube. The differential amplifier cancels equal intensity components leaving only the scattered light and the uncorrelated noise to be seen by the oscilloscope. RCA 7102 photomultiplier tubes are used for detection. The characteristics of the RCA 7102 tube can be found in Ref. 5. The external trigger used is a HP 5082-4205 pin diode. The diode output can be either connected to the external trigger input plugin or to a signal input if it is desirous to monitor the laser pulse.

B. ALIGNMENT PROCEDURE

As in any optical experiment success or failure depends on the proper alignment of the equipment. After attempting many different methods, the one used in Figure 6 was found to be the easiest and most accurate. The ruby laser is the first instrument to be aligned. The Helium-Neon laser is first aligned so that its beam strikes the center of the windows on both sides of the plasma machine. The Helium-Neon laser passes through the plasma 3 cm. from the cathode. Next, the ruby laser is placed in position so that it can be leveled to be parallel to the Helium-Neon laser beam. Without the ruby rod in place, the Helium-Neon laser light should pass through the front lens, go between the flashtubes, centered both vertically and horizontally, and hit the rear prism so that the light returns along the same path. The initial alignment is correct if only one red spot is seen on the front mirror, rear prism, both windows of the plasma machine and the light is reflected back into the Helium-Neon laser. The ruby rod can now be put into place. The ruby rod should be adjusted so that it has the Helium-Neon laser light passing on a line through its center. The reflection from the front of the ruby rod should hit at the same point as all other reflections (from the prism and the front mirror). If when test fired, the laser light leaves a burn pattern on a piece of polaroid film of the same size and shape as the ruby rod, the laser is now properly aligned. The output periscope must be aligned so that it is at a right angle to the Helium-Neon laser light and is focused on the plasma beam. For the alignment of the periscope, an aluminum welding rod is inserted through the hollow cathode so that it simulates the plasma beam. The periscope is now aligned by observing the reflection of the Helium-Neon laser light off the welding rod. The

periscope is adjusted so that it, in conjunction with lens B, focuses the light on the input slit of the monochromator. If lens A and lens B are properly adjusted, an image of the welding rod will be seen on the input slit of the monchromator. With the laboratory completely dark (reflected light of Helium-Neon laser is weak) the path of the light beam may be checked step by step with a piece of white paper so that the beam splitter can be adjusted. The extraordinary and ordinary beams go to separate photomultipliers. The alignment of the optical system, less the ruby laser, may now be checked by turning the plasma beam on and following the emitted light to the photomultipliers. If the system is properly aligned, the oscilloscope will show a trace of only uncorrelated noise of which the majority is photomultiplier noise.

C. CALIBRATION

1. Optics Technology, Model 130, Ruby Laser [Ref. 6].

The laser used in this experiment was an Optics Technology, Model 130, High Peak Power Q-switched Laser. The characteristics of the laser are listed in Figure 7. As mentioned in the Introduction in the non Q-switched mode it is a reliable instrument and has a reproducible pulse width and energy level. However, a true drawback with this laser is the liquid dye Q-switch. A liquid dye Q-switch has inherent in it a fast degradation time and will allow multiple lasing if it is not replaced after every two or three firings. The laser in the non Q-switch mode may be fired twice a minute but this must be lengthened to once every two to five minutes depending on the power level used when in the Q-switched mode. The increased time between firings is due to the increased heating of the ruby rod when firing in the Q-switched mode. The ruby laser is calibrated using the method suggested by Korad Company [Ref. 7]. The

Model K-D1 Photodiode [Ref. 8] is used in conjunction with the Model K-J3 Laser Calorimeter to calibrate the Model K-D1's output on the oscilloscope. Figure 8 show the calibration setup. The laser is fired into the calorimeter with ~ 1% of the beam being deflected to the MgO block which puts diffuse light into the photodiode. The photodiode has both power and energy outputs. The power output is displayed on a fast oscilloscope, Tektronix 519 to measure the pulse width. The energy output is displayed on a second oscilloscope to show the peak energy in volts. The calorimeter output is sent through a milli-microvoltmeter [Ref. 9] to a x - y plotter [Ref. 10]. Sketches of actual calorimeter plots are shown in Figure 9. By using the relationship

$$J = V_p R$$

where J = energy in joules

V_p = peak voltage in microvolts

R = responsivity in joules/microvolt

the calorimeter output can be converted to joules of energy. It is now possible to plot a graph of calorimeter output (joules) versus photodiode output (volts) to find the proper conversion factor so that further use of the calorimeter is unnecessary. Figure 10 shows the calibration curve for the Model 130 laser. It should be noted that once calibration is accomplished, the slope will remain constant and recalibration is unnecessary if the equipment is moved. By plotting one point the calibration curve can be drawn by using the already computed slope. From the calibration curve we obtain the relationship

$$\text{joules} = (1.05 \times 10^{-1}) (\text{voltage} - 5.1).$$

The pulse width of the non Q-switched laser was found to be 0.4 milliseconds. Q-switched it was 25-35 nanoseconds.

2. Monochromator

A Model 98, Single Beam, Single Pass, Infrared Monochromator was used [Ref. 11]. The monochromator was calibrated at a slit micrometer setting of 0.5. The units of calibration are wavelength in terms of drum setting. The monochromator was calibrated by using a helium discharge lamp and a Bausch and Lomb calibrated monochromator [Ref. 12] with a tungsten filament source. A RCA 7120 photomultiplier in conjunction with a Taktronix 545A oscilloscope was used to measure the output of the various helium spectral lines. Figure 11 shows the results. The relationship between dial and wavelength is 1 unit on monochromator equals 11.5 A. Next the Bausch and Lomb Monochromator was used as a source to find an approximate value for the observed helium wavelengths. By using the Bausch and Lomb settings and a table containing the Helium spectral lines [Ref. 13] it was possible to identify the lines in the vicinity of the ruby wavelength. The Bausch and Lomb source was verified by the use of the Helium-Neon laser which has a wavelength of 6328 Å.

V. CONCLUSIONS

A. RESULTS

The one favorable result of this experiment was the ability of the differential amplifier detection system to cancel the plasma radiation. Since the plasma radiation is much stronger than the scattered light and must be separated from the scattered laser light, this does show that the system is usable. Most of the work done was with the laser in the non-Q-switched mode because a dual sweep, fast rise time oscilloscope with a differential capability was not available. A differential comparator amplifier, Tektronix 7A13 of the new 7000 series of oscilloscopes, with a rise time of 3.5 ns and a deflection factor of 1 mV was ordered in January with an expected delivery time of 6 months. The use of this amplifier should facilitate the experiment. Also, to add dye to the liquid dye Q-switch, after the laser was put into position, was for the most part impossible without disturbing the laser alignment. This was due to the fact that the air hose for cooling and the cover of the laser had to be removed. Ideally none of the equipment should be touched after alignment has been accomplished until all data have been taken. Although no scattered signal from the plasma was obtained, there were many reflections from the plasma machine to the detecting apparatus. All the reflections except internal reflections in the plasma machine were reduced when the laser was put opposite the detection apparatus. There will always be some internal reflections, but they can be held to a minimum by laser beam dumps. By reversing the input ports on the sides of the plasma machine, it was possible to substantially decrease these reflections.

B. RECOMMENDATIONS

1. The experimental setup as shown in Figure 5 should be used for future experiments because of the ability to cancel the plasma radiation.

2. A water-cooled laser head is in the process of being made at the Plasma Facility. There is available a power supply with the capability of producing 200 MW of laser power in the Q-switched mode. A Pockel's Cell Q-switch will have to be purchased for the laser. This laser should greatly enhance the chances of successful scattering experiments.

3. A beam dump in the form of a light trap should be made for the port opposite the laser. It should be designed with the intention of using it at any port on the section of the plasma machine where scattering experiments are being conducted.

4. Photodiodes should be used for detection because of their high signal to noise ratio. This will necessitate refocusing the light from the beam splitter onto the diodes.

5. As mentioned in Section II the ratio of scattered to incident light is dependent on dz (length observed in the plasma) and $d\Omega$ (the solid angle observed). To maximize the scattered to incident power it is necessary to have a large angle of observation, keeping in mind that the increased plasma radiation will be canceled out. The solid angle, $d\Omega$, can be increased by increasing the exit port so that a lens of larger cross sectional area can be used to observe the plasma. The lens should have a small focal length to get a large $d\Omega$. The image of the length of plasma observed, dz, can be maximized by using a lens of shorter focal length for refocusing the light on the monochromator.

$$\frac{dz}{\text{focal length of lens at plasma}} = \frac{\text{monochromator slit opening}}{\text{focal length of lens at monochromator}}$$

6. This experiment should be continued because it is possible to obtain information (density and temperature) by using scattering experiments. The successful completion of this experiment will greatly enhance the work done in other areas such as in the studying of laser produced plasmas and in the studying of the shock wave of the θ-Pinch.

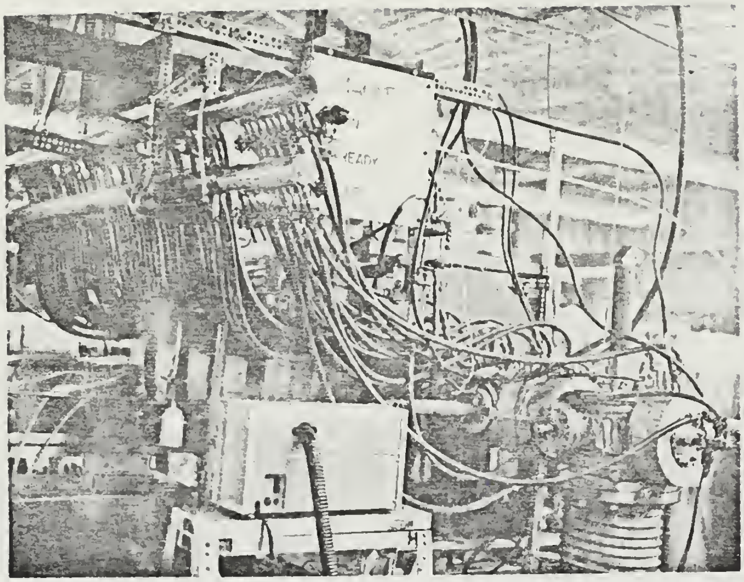


Figure 1

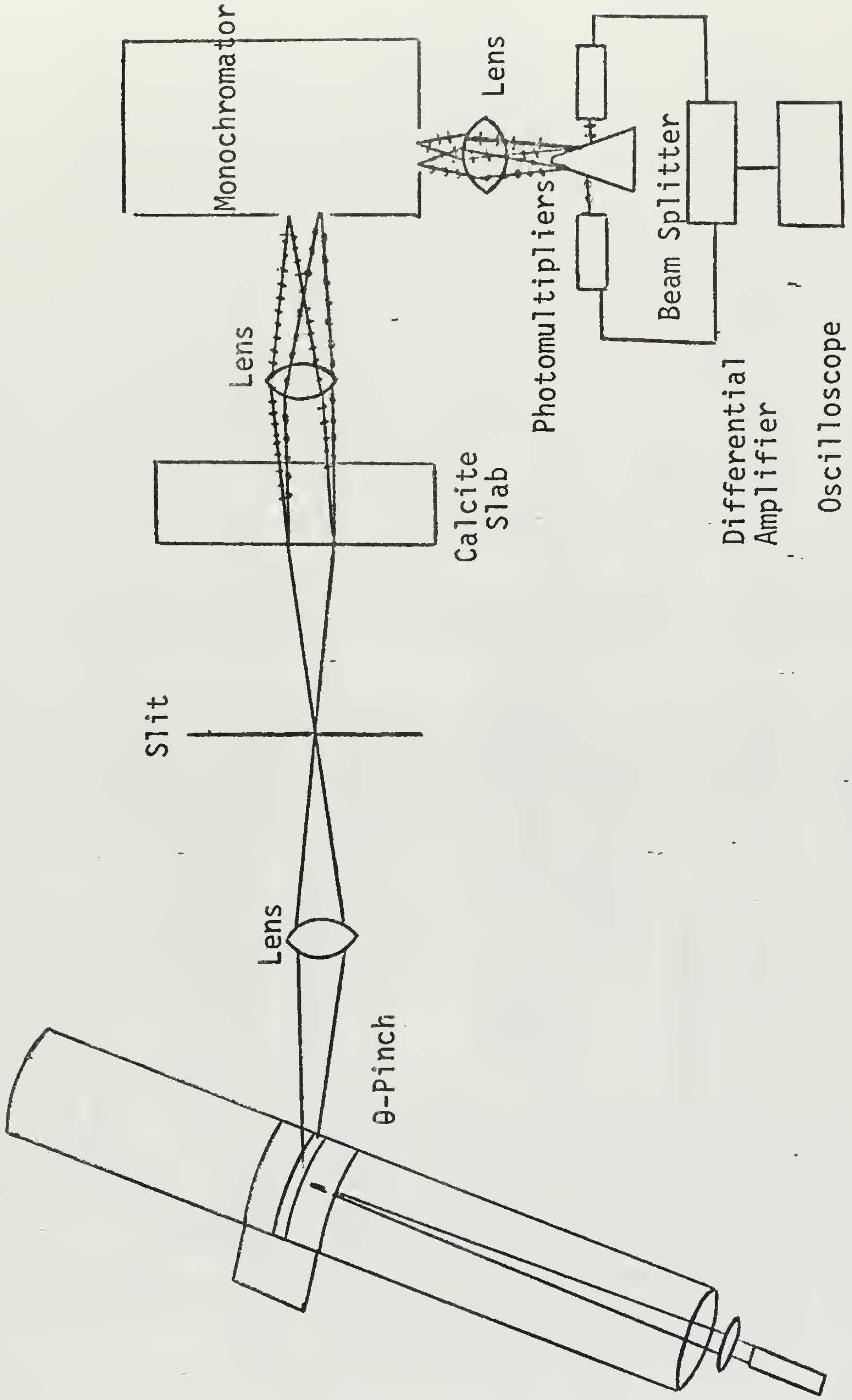
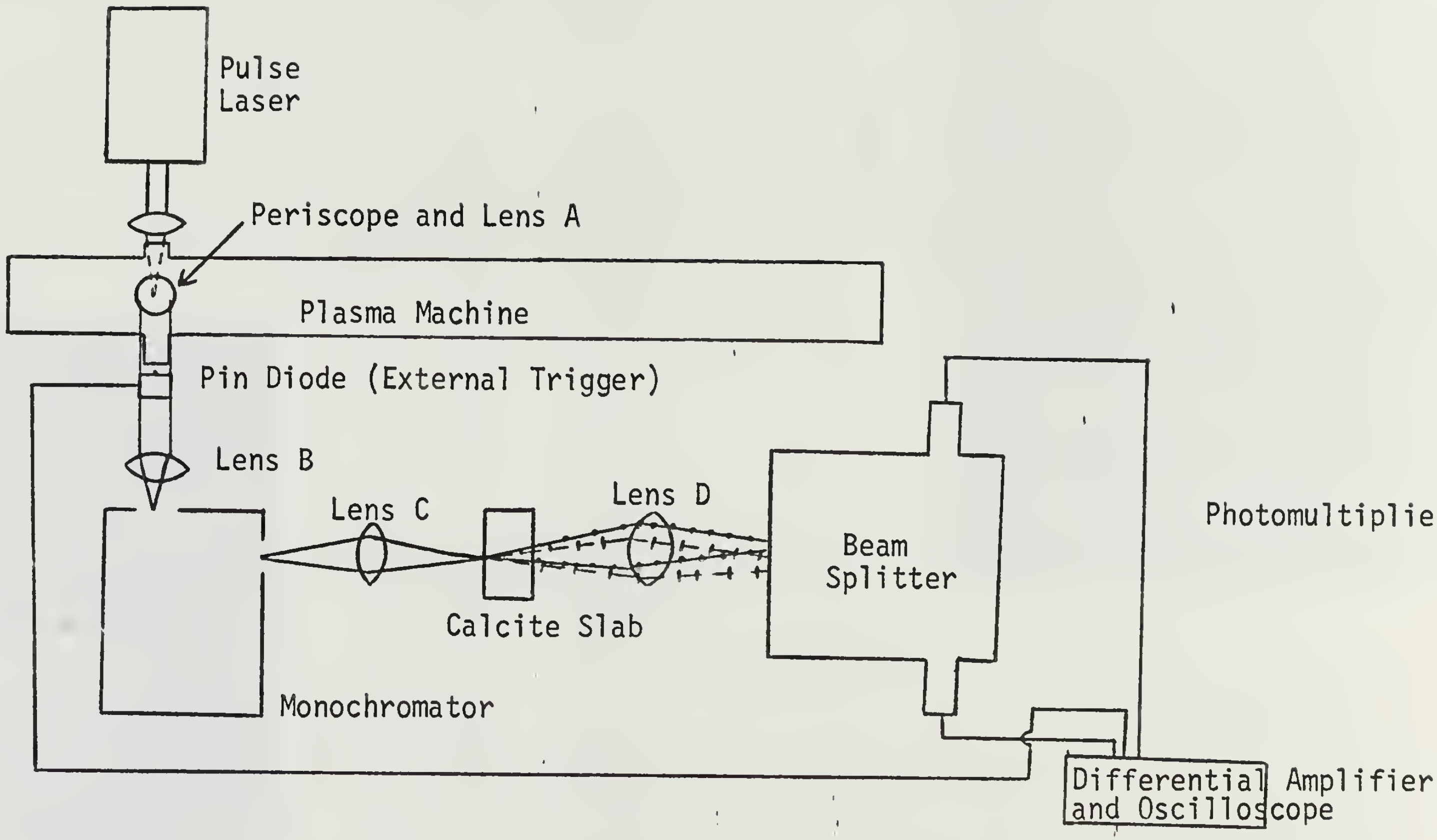

Monochromator
Lens
Photomultipliers
Beam Splitter
Lens
Calcite
Slab
Differential
Amplifier
Oscilloscope
Slit
Lens
θ-Pinch

Figure 2



Pulse
Laser
Periscope and Lens A
Plasma Machine
Pin Diode (External Trigger)
Lens B
Lens C
Lens D
Calcite Slab
Beam
Splitter
Photomultipliers
Monochromator
Differential Amplifier
and Oscilloscope

Figure 3

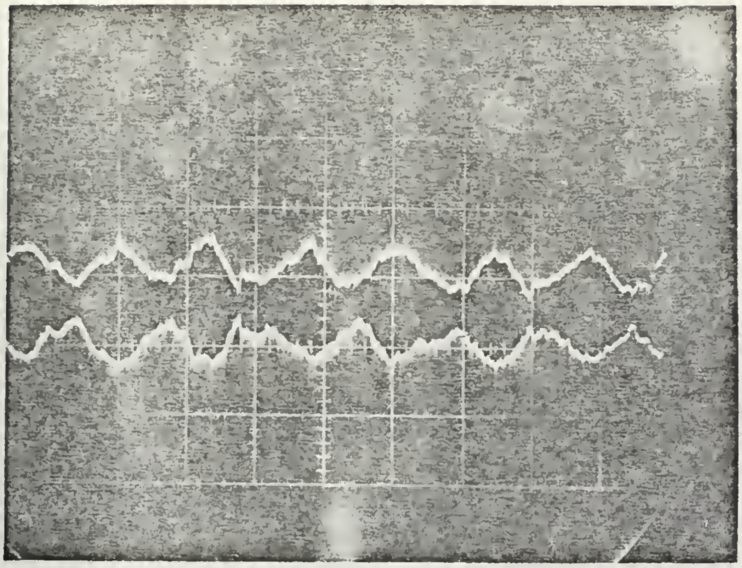


Figure 4

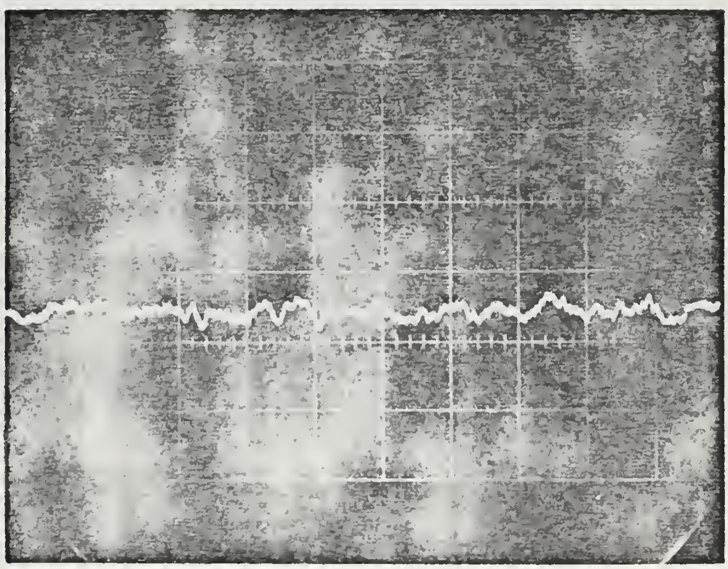
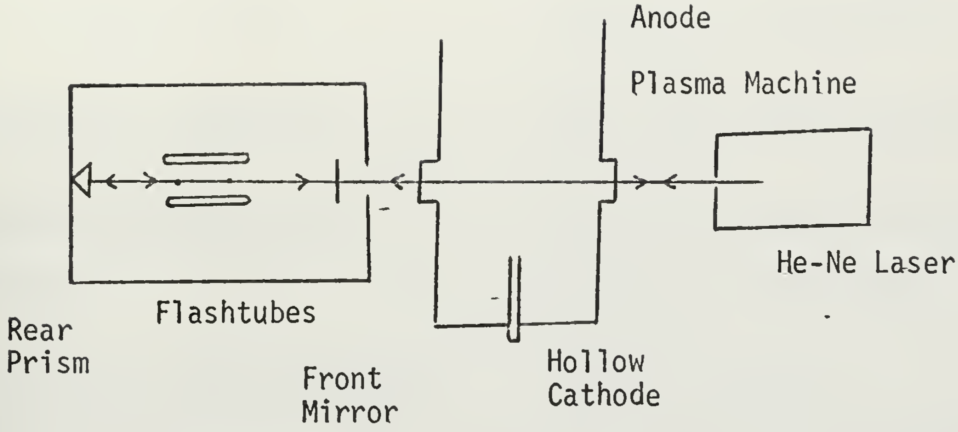


Figure 5


Anode
Plasma Machine
He-Ne Laser
Flashtubes
Rear Prism
Front Mirror
Hollow Cathode

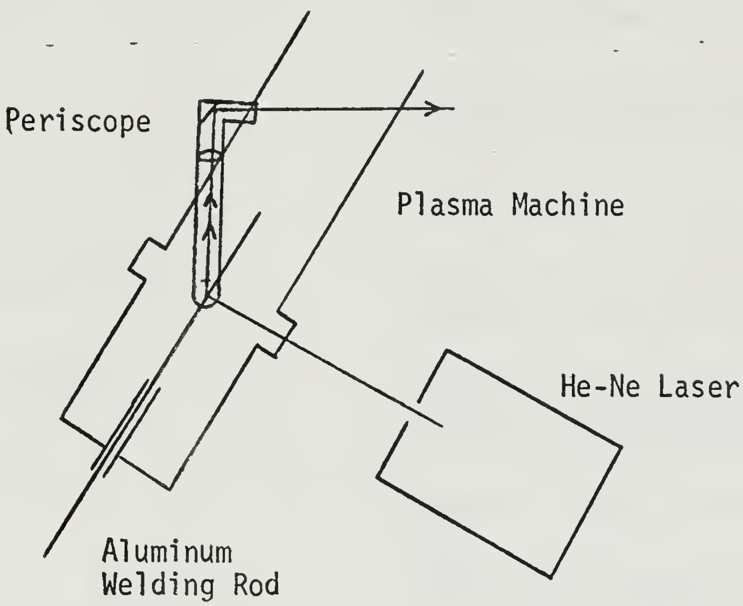

Periscope
Plasma Machine
He-Ne Laser
Aluminum Welding Rod

Figure 6

Wavelength	6943 Angstroms.
Peak Power, Q-Switched	Variable from approximately 10 to 100 megawatts, bleachable liquid Q-switching.
Pulse Width, Q-Switched	Experimental found to be from 25-35 nanoseconds.
Maximum Repetition Rate	May be fired every 30 seconds.
Divergence	Less than 10 milliradians, Q-switched.
Output Energy, Non-Q-Switched	Typically 5 Joules.
Pulse Width, Non-Q-Switched	Approximately 0.2 milliseconds.
Laser Crystal	Production quality, 60° orientation, 3/8" x 3" ruby crystal for 6943 Angstroms. Ruby crystal is mounted in a cylinder of UV absorbing material, which prevents the migration of the doping centers and thereby insures optimum life of the ruby.
Pumping Lamps	Two linear Xenon arc lamps.
Laser Cavity	Closely coupled configuration with polished aluminum inner surface and length of 3-5/8".
Cooling	Forced air from a high capacity blower.
Bleachable Liquid Cell	Spectrographic type optical cell mounted on locating plate.
Laser Power Supply	Storage level variable to 2500 Joules. Capacitance-800 microfarads. Maximum voltage-2500 volts.
Size	Head-17" deep by 7" wide by 12" high. Power Supply/Console-22" deep by 23" wide by 35" high.

Figure 7 [Ref. 6]

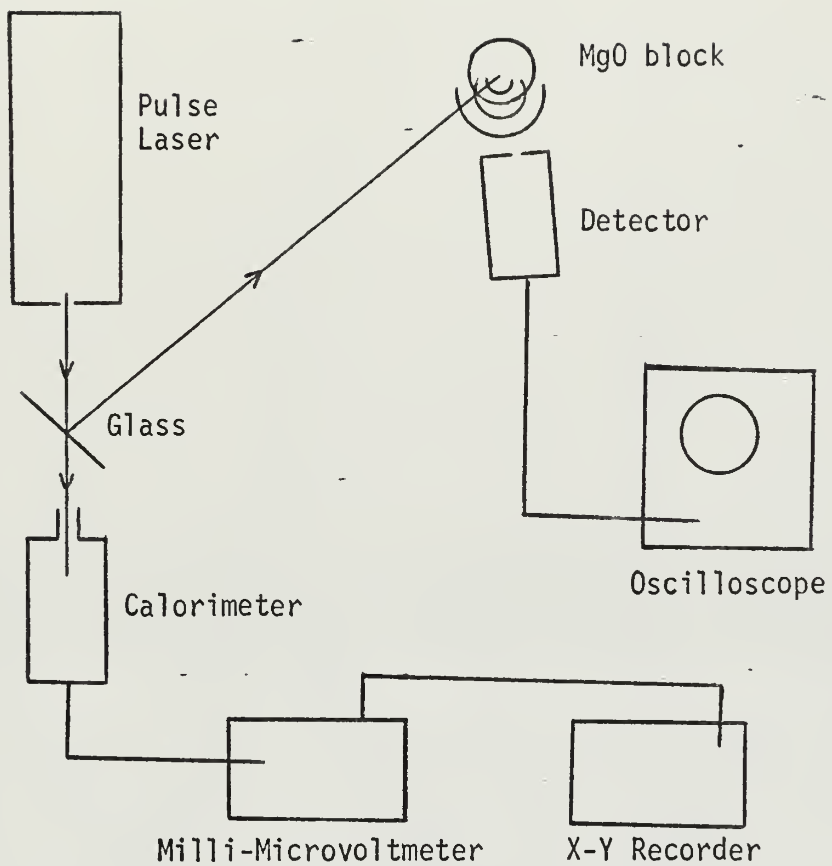

MgO block
Pulse
Laser
Detector
Glass
Oscilloscope
Calorimeter
Milli-Microvoltmeter
X-Y Recorder

Figure 8

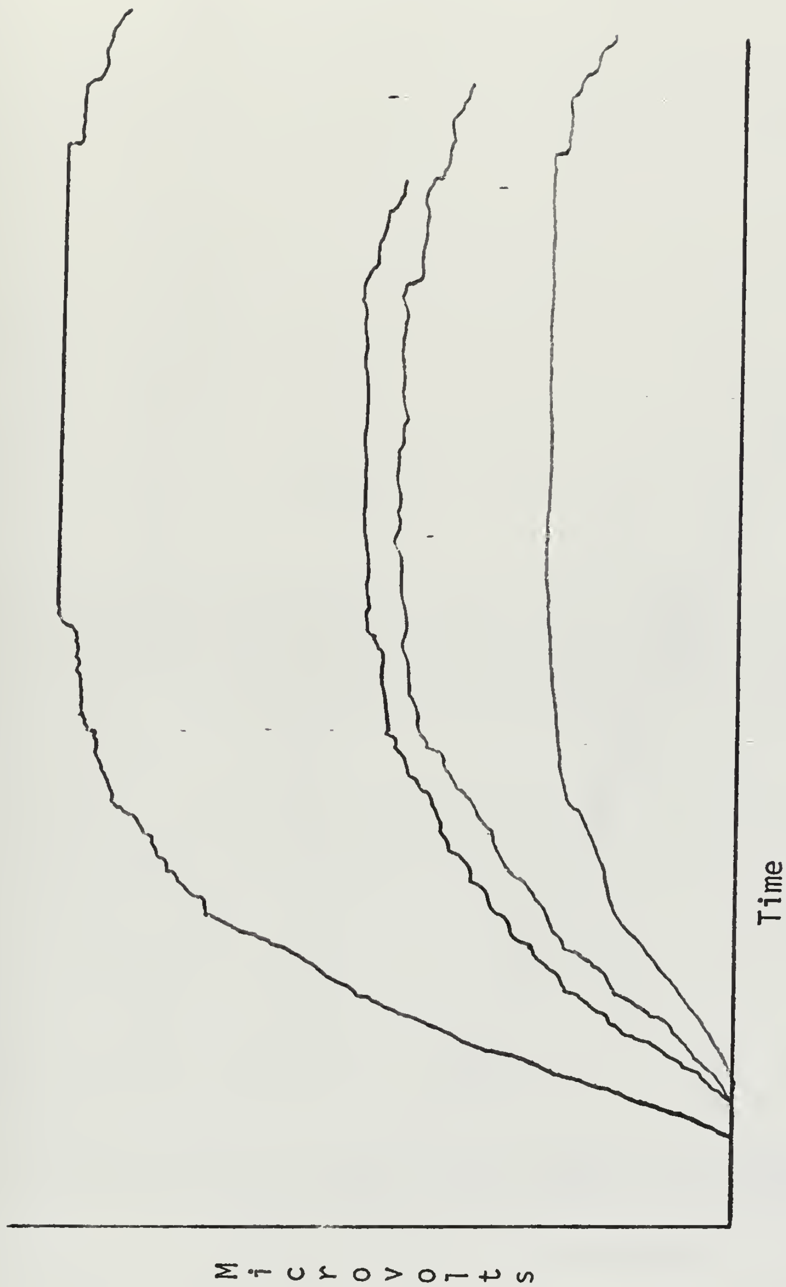
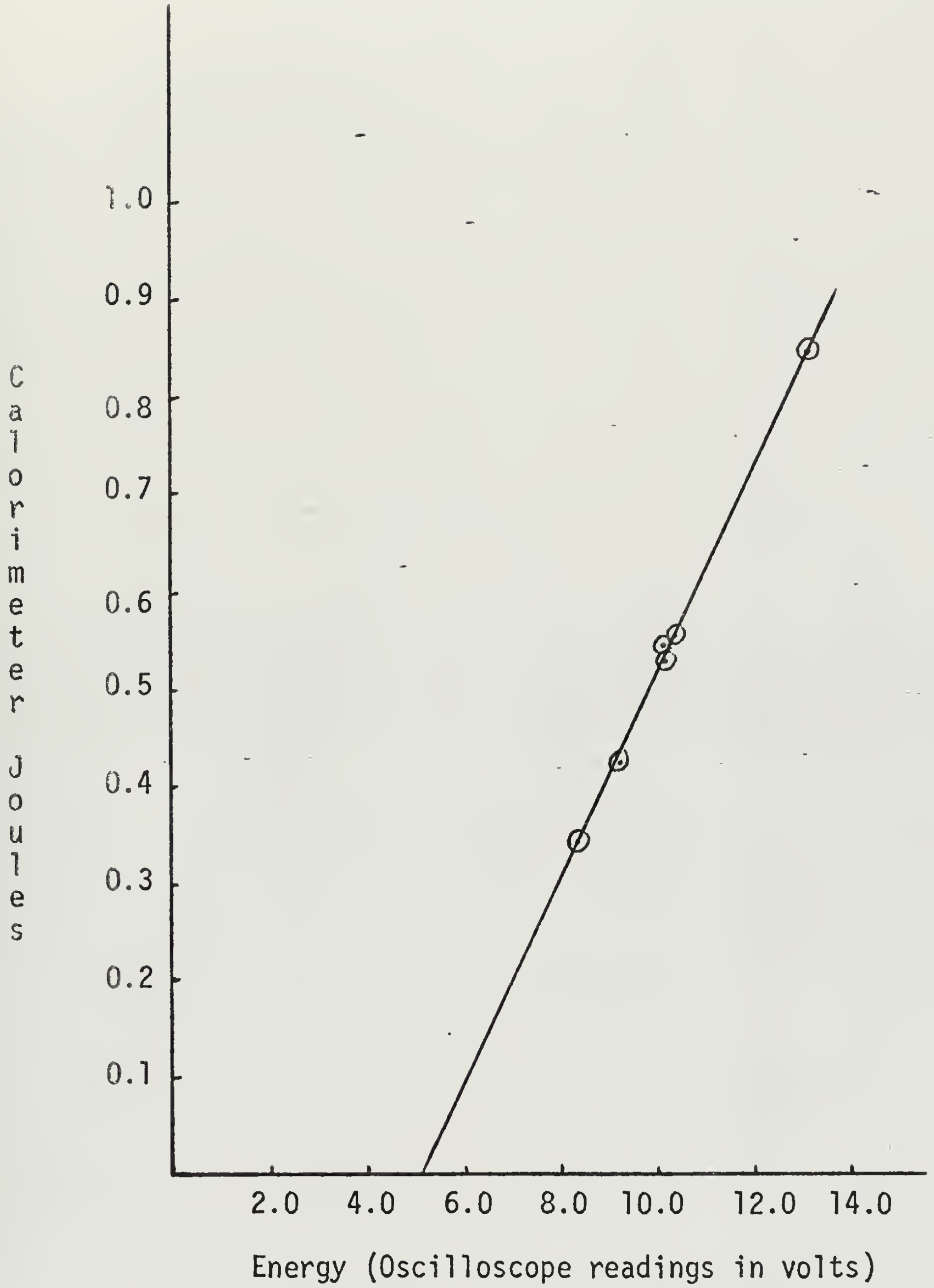


Figure 9



Calorimeter Joules
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Energy (Oscilloscope readings in volts)

Figure 10

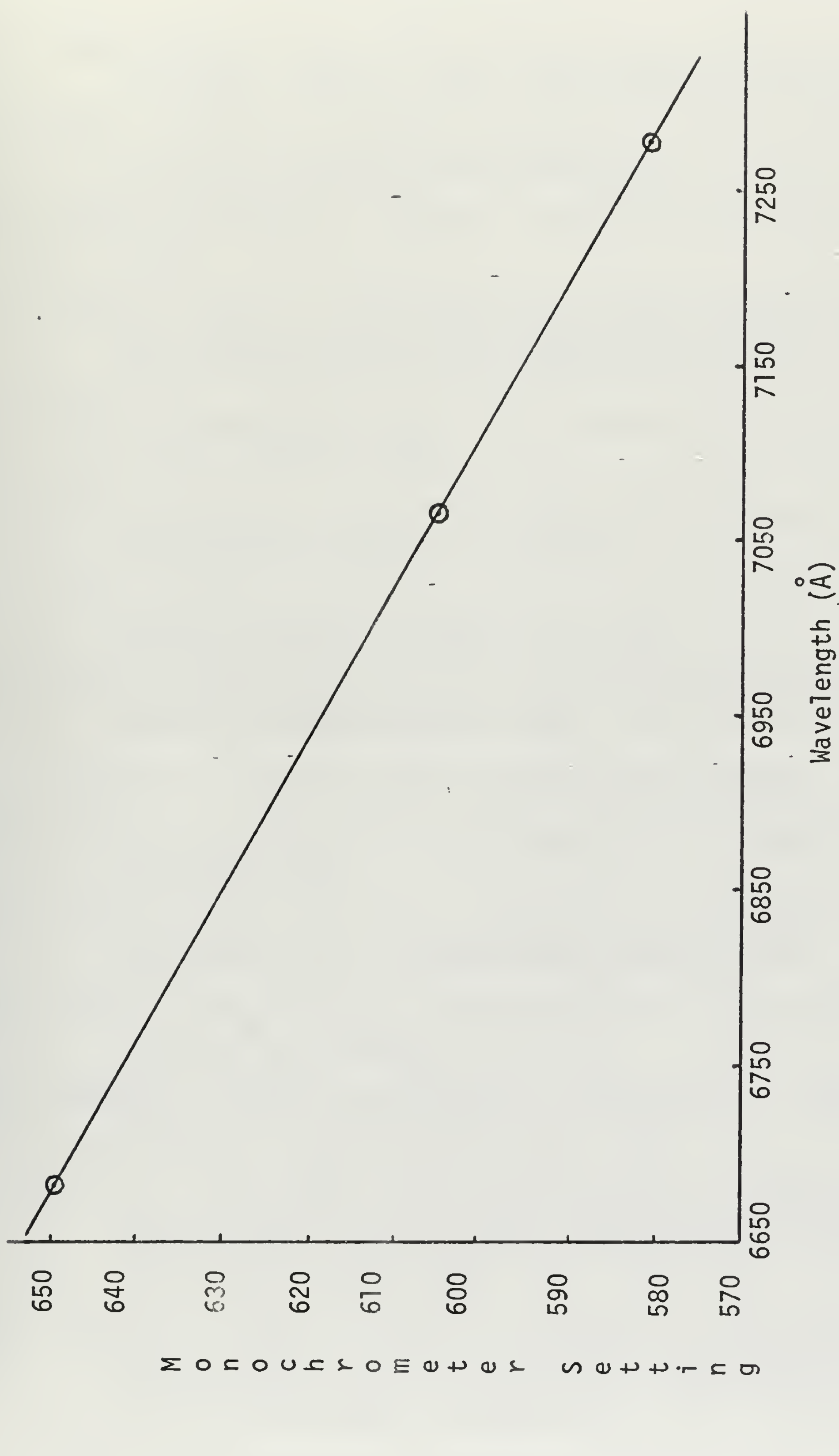

Monochrometer Setting
650
640
630
620
610
600
590
580
570
6650
6750
6850
6950
7050
7150
7250
Wavelength (Å)

Figure 11

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13. ABSTRACT

This experiment was conducted to learn experimental techniques for studying Thomson Scattering at an angle of 90° from a laboratory plasma. A successful method of canceling the plasma radiation was employed by using a Calcite Slab to separate the plasma radiation into two equal intensity beams which self canceled when put through a differential amplifier. Scattered light from the plasma was not observed due to the noise level of the photomultipliers and the reflections from the plasma chamber.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Laser Light Scattering						
Low Signal to Noise Detection						

Thesis 118844
A376 Alger
c.1 90° laser light
scattering from a
low density plasma.